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Limits on Low Scale Gravity from $e^+e^- \rightarrow W^+W^-, ZZ$ and $\gamma\gamma$ ¹

K. Agashe² and N.G. Deshpande³

*Institute of Theoretical Science
5203 University of Oregon
Eugene OR 97403-5203*

Abstract

It has been proposed recently that the scale of quantum gravity (“the string scale”) can be $M_S \sim \text{few TeV}$ with $n \geq 2$ extra dimensions of size $R \lesssim \text{mm}$ so that, at distances greater than R , Newtonian gravity with $M_{Pl} \sim 10^{18} \text{ GeV}$ is reproduced if $M_{Pl}^2 \sim R^n M_S^{n+2}$. Exchange of virtual gravitons in this theory generates higher-dimensional operators involving SM fields, suppressed by powers of M_S . We discuss constraints on this scenario from the contribution of these operators to the processes $e^+e^- \rightarrow W^+W^-, ZZ, \gamma\gamma$. We find that LEP2 can place a limit $M_S \approx 1 \text{ TeV}$ from $e^+e^- \rightarrow W^+W^-, ZZ, \gamma\gamma$.

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²email: agashe@oregon.uoregon.edu

³email: desh@oregon.uoregon.edu

1 Introduction

A new framework to solve the gauge hierarchy problem of the Standard Model (SM) has recently been proposed by Arkani-Hamed, Dimopoulos, Dvali [1]: the scale at which the gravitational interactions become comparable in strength to the ordinary gauge interactions (“the string scale”), M_S , is close to the weak scale, m_W , *i.e.*, $\sim \text{TeV}$. The ultraviolet cut-off for the quadratically divergent quantum corrections to the Higgs (mass)² is then $\sim \text{TeV}$, thus stabilizing the weak scale. In other words, there is no hierarchy to begin with since the only fundamental scale is the weak scale $m_W \sim \text{TeV}$.

To get the Newtonian $1/r$ gravitational potential with scale $M_{Pl} \sim 10^{18} \text{ GeV}$, it is proposed that there are n extra dimensions of size R . The “Planck scale” in $(4+n)$ dimensions is $\sim M_S \sim 1 \text{ TeV}$, but the SM particles propagate only in the usual 4 dimensions while gravitons (and perhaps other particles) propagate in $(4+n)$ dimensions. Thus, for $r \ll R$, the gravitational potential is modified from the usual one whereas for $r \gg R$, using Gauss’ law, we can see that the Newtonian $1/r$ potential is recovered with the scale M_{Pl} if the following relation between n and R is satisfied [1]:

$$M_{Pl}^2 \sim R^n M_S^{n+2}. \quad (1)$$

If $n = 1$, R is too large and is ruled out since gravity is then modified over solar system distance scales. For $n \geq 2$, we get $R \lesssim \text{mm}$. Gravity has been measured at present only to distance scales $\sim \text{mm}$.

From the $(4+n)$ dimensional point of view, the gravitons couple to the SM fields with strength given by powers of $(1/M_S)$, thus inducing (from graviton exchange) higher-dimensional operators involving SM fields, suppressed by powers of M_S . Seen from the 4 dimensional point of view, a graviton with momentum in the n compact dimensions (of size R) behaves as a particle with mass $\sim 1/R$. Each graviton couples to the SM fields with strength suppressed by powers of the 4 dimensional Planck scale, M_{Pl} . However, there is a large multiplicity of these graviton states since we have to sum over all possible

momenta in the n dimensions. This tower of Kaluza-Klein graviton states results in an enhancement of this coupling to powers of $(1/M_S)$ [1].

Since the gravitons couple to all SM particles, the s , t and u -channel exchange of virtual gravitons mediates processes like $f\bar{f}$, $VV \rightarrow f'\bar{f}'$, $V'V'$ (where f are fermions and V are gauge bosons), e (or ν) $q \rightarrow e$ (or ν) q etc. [2, 3, 4, 5].

In this letter, we study the contribution of the virtual graviton exchanges in these theories with quantum gravity at the weak scale to the processes $e^+e^- \rightarrow W^+W^-$, ZZ , $\gamma\gamma$ at LEP2 and at a future Linear Collider (LC).

2 Matrix Elements

The matrix element for

$$e^+ (p_+) e^- (p_-) \rightarrow V (k_1) \bar{V}_2(k_2) \quad (2)$$

from graviton exchange (neglecting the electron mass) is given by [2, 3] (we use Eqn.(71) of Han, Lykken, Zhang in [3])

$$\begin{aligned} \mathcal{M}_{gravity} = & \lambda \frac{4}{M_S^4} [2 (p_- \cdot k_2 - p_- \cdot k_1) (\varepsilon_1^* \cdot \varepsilon_2^*) \bar{v} \not{k}_1 u \\ & + 2 (p_- \cdot \varepsilon_1^*) (k_1 \cdot \varepsilon_2^*) \bar{v} \not{k}_1 u - 2 (p_- \cdot \varepsilon_2^*) (k_2 \cdot \varepsilon_1^*) \bar{v} \not{k}_1 u \\ & - 2 (p_- \cdot k_2) (k_1 \cdot \varepsilon_2^*) \bar{v} \not{\varepsilon}_1^* u - 2 (p_- \cdot k_1) (k_2 \cdot \varepsilon_1^*) \bar{v} \not{\varepsilon}_2^* u \\ & + s (p_- \cdot \varepsilon_2^*) \bar{v} \not{\varepsilon}_1^* u + s (p_- \cdot \varepsilon_1^*) \bar{v} \not{\varepsilon}_2^* u], \end{aligned} \quad (3)$$

where the momenta are of the incoming e 's and the outgoing bosons, the ε 's are the polarization vectors of the gauge bosons and \bar{v} , u are the e^+ , e^- spinors, s and t denote the Mandelstam variables. The scale M_S is chosen to agree with the notation used by Hewett in [4] (see Eqns.(61) and (5) of [3] and [4], respectively). The factor λ as in [4] incorporates any model-dependence (*i.e.*, it depends on the full theory – we will assume that it is ± 1). So, strictly

speaking, our limits are on $|\lambda|^{-1/4} M_S$.⁴

The helicity amplitudes, $\mathcal{M}(\kappa, \varepsilon_1, \varepsilon_2, s, t)$, *i.e.*, the amplitudes for given helicity κ of e^- (we neglect the electron mass and assume that the helicities of the electron and the positron are opposite) and given polarizations of the gauge bosons, can be written in terms of a set of 12 linearly independent matrix elements⁵ (6 for each κ), denoted by \mathcal{M}_i^κ ($i = 1$ to 6) with coefficient functions $F_i(s, t)$ (see, for example, Beenakker, Denner in [6]):

$$\mathcal{M}(\kappa, \varepsilon_1, \varepsilon_2, s, t) = \sum_i \mathcal{M}_i^\kappa(\varepsilon_1, \varepsilon_2, s, t) F_i^\kappa(s, t). \quad (4)$$

The \mathcal{M}_i^κ are the linearly independent Lorentz and CP-invariant objects which can be formed from \bar{v} , u , $\varepsilon_{1,2}$ and the momenta of the particles. These basic matrix elements contain only kinematical information and the complete dependence on the polarizations. The coefficient functions (which also have to be Lorentz and CP-invariant) contain all the dynamics and are independent of the polarizations.

In the SM, the Born helicity amplitude for $e^+e^- \rightarrow W^+W^-$ is;

$$\mathcal{M}_{Born}^{SM} = \frac{e^2}{2s_W^2 t} \mathcal{M}_1^\kappa \delta_{\kappa-} + e^2 \left[\frac{1}{s} - \frac{c_W}{s_W} g_{eeZ}^\kappa \frac{1}{s - M_Z^2} \right] 2(\mathcal{M}_3^\kappa - \mathcal{M}_2^\kappa), \quad (5)$$

where the first term is from t -channel ν exchange ($\delta_{\kappa-} = 1$ for $\kappa = -1/2$ and 0 for $\kappa = +1/2$) and the second term is from s -channel Z and γ exchange. The electron- Z coupling is

$$g_{eeZ}^\kappa = \frac{s_W}{c_W} - \delta_{\kappa-} \frac{1}{2s_W c_W}. \quad (6)$$

The \mathcal{M}_i^κ 's are given by

$$\mathcal{M}_1^\kappa = \bar{v}(p_+) \not{\varepsilon}_1^* (\not{k}_1 - \not{p}_+) \not{\varepsilon}_2^* \omega_\kappa u(p_-)$$

⁴It is possible that (depending on the full theory) other tree level diagrams or loop diagrams generate other higher-dimensional operators which may also contribute to the process $e^+e^- \rightarrow V\bar{V}$. In this case, the limits on M_S will be modified.

⁵We assume CP invariance.

$$\begin{aligned}
\mathcal{M}_2^\kappa &= \bar{v}(p_+) \frac{k_1 - k_2}{2} (\varepsilon_1^* \cdot \varepsilon_2^*) \omega_\kappa u(p_-) \\
\mathcal{M}_3^\kappa &= \bar{v}(p_+) [\not{\varepsilon}_1^* (\varepsilon_2^* \cdot k_1) - \not{\varepsilon}_2^* (\varepsilon_1^* \cdot k_2)] \omega_\kappa u(p_-),
\end{aligned} \tag{7}$$

where ω_κ is the helicity projection operator. We rewrite the gravity matrix element in Eqn.(3) in terms of the \mathcal{M}_i . After some manipulations, we get:

$$\mathcal{M}_{gravity} = \frac{4}{M_S^4} [s\mathcal{M}_1^\kappa - s(1 - \beta \cos \theta) (\mathcal{M}_3^\kappa - \mathcal{M}_2^\kappa)], \tag{8}$$

where $\beta = \sqrt{1 - 4M_V^2/s}$ is the velocity of the V bosons in the cm frame ($V = W, Z, \gamma$) and θ is the angle between e^+ and V in the cm frame, *i.e.*, the effect of the graviton exchange is to modify the coefficient functions $F_{1,2,3}$ and no new basic matrix element is generated.

The differential cross section for unpolarized electrons and positrons and W 's is given by

$$\left(\frac{d\sigma}{d\cos\theta} \right) = \frac{\beta}{128\pi s} \sum_{\kappa, \varepsilon_+, \varepsilon_-} | \mathcal{M}(\kappa, \varepsilon_+, \varepsilon_-, s, t) |^2 \tag{9}$$

with $\mathcal{M}(\kappa, \varepsilon_+, \varepsilon_-, s, t) = \mathcal{M}_{Born}^{SM}(\kappa, \varepsilon_+, \varepsilon_-, s, t) + \mathcal{M}_{gravity}(\kappa, \varepsilon_+, \varepsilon_-, s, t)$. To evaluate the cross sections, it is convenient to use the following expressions for \mathcal{M}_i for each $\kappa, \varepsilon_{+,-}$ in terms of s, θ and M_W where θ is the angle between e^+ and W^+ in the cm frame (these are from the appendix of [6]):

$$\mathcal{M}_1^\kappa(\pm, \mp) = 2E^2 \sin \theta (\cos \theta \mp 2\kappa), \tag{10}$$

$$\begin{aligned}
\mathcal{M}_1^\kappa(\pm, \pm) &= 2E^2 \sin \theta (\cos \theta - \beta), \\
\mathcal{M}_2^\kappa(\pm, \pm) &= 2\beta E^2 \sin \theta,
\end{aligned} \tag{11}$$

$$\begin{aligned}
\mathcal{M}_1^\kappa(\pm, 0) &= \mathcal{M}_1^\kappa(0, \mp) = \frac{\sqrt{2}E}{M_W} E^2 (\cos \theta \mp 2\kappa) [2\beta - 2\cos \theta \mp 2\kappa(1 - \beta^2)], \\
\mathcal{M}_3^\kappa(\pm, 0) &= \mathcal{M}_3^\kappa(0, \mp) = \frac{\sqrt{2}E}{M_W} 2\beta E^2 (\cos \theta \mp 2\kappa),
\end{aligned} \tag{12}$$

$$\begin{aligned}
\mathcal{M}_1^\kappa(0,0) &= \frac{E^2}{M_W^2} 2E^2 \sin \theta [3\beta - \beta^3 - 2 \cos \theta], \\
\mathcal{M}_2^\kappa(0,0) &= \frac{E^2}{M_W^2} 2\beta E^2 \sin \theta (1 + \beta^2), \\
\mathcal{M}_3^\kappa(0,0) &= \frac{E^2}{M_W^2} 8\beta E^2 \sin \theta,
\end{aligned} \tag{13}$$

where \pm denote the transverse polarizations and 0 denotes longitudinal polarization, E is the beam energy and the matrix elements $\mathcal{M}_{i=2,3}^\kappa$ vanish for the combinations of the polarizations not given above (for example, $\mathcal{M}_2^\kappa(+, -) = 0$).

Radiative corrections due to virtual γ , Z , W exchange to the SM and graviton exchange amplitude and hence the SM cross section are about 3% $\sim O(\alpha/(4\pi))$ (since the corrections to the cross section are from interference with the Born amplitude). These corrections should change the effect of graviton exchange on the cross section (which is small to begin with) by about the same percent since the graviton exchange effect is from interference with the SM amplitude.⁶ We neglect this effect. The error on the theoretical prediction in the SM, including radiative corrections, is about 6 fb for the WW case which is much smaller than the experimental (statistical) error at LEP2 and comparable to, but still smaller than the statistical error at the LC and hence we neglect this theoretical error as well.

A similar analysis can be done for $e^+e^- \rightarrow ZZ$. In terms of \mathcal{M}_i^κ , the SM Born amplitude from t and u channel e exchange is:

$$\mathcal{M}_{Born}^{SM} = \left[\frac{e}{s_W c_W} \left(s_W^2 - \frac{1}{2} \delta_{\kappa-} \right) \right]^2 \left[\left(\frac{1}{t} + \frac{1}{u} \right) \mathcal{M}_1^\kappa + 2 \frac{1}{u} (\mathcal{M}_2^\kappa - \mathcal{M}_3^\kappa) \right]. \tag{14}$$

The graviton exchange matrix element is given by Eqn.(8) with $\beta = \sqrt{1 - 4 M_Z^2/s}$. The expressions for the basic matrix elements are the same as Eqns.(10–13) with M_W replaced by M_Z .

⁶The corrections due to emission of real soft/collinear photons will mostly cancel in the ratio of the shift of the cross section due to graviton exchange to the SM cross section, *i.e.*, in the percent deviation due to graviton exchange.

3 Limits on M_S

In Fig.1, we show the differential cross section for the SM case and with $M_S = 500$ GeV. The SM cross section peaks in the forward direction due to the t -channel ν exchange diagram. We see that the effect of the graviton exchange is to reduce the cross section for all θ , if $\lambda > 0$ in Eqn.(3) (as assumed in Fig.1) and to increase it for all θ if $\lambda < 0$. So, the deviation of the total cross section from the SM prediction will give a better Confidence Level (CL) search reach for the graviton exchange amplitude and hence will give a better limit on M_S . The combined (all 4 detectors) LEP2 measurement at $\sqrt{s} = 183 - 189$ GeV is $\sigma_{WW} \approx 16 \text{ pb} \pm 0.4 \text{ pb}$ [7]. We get a 2σ limit of $M_S \approx 665$ GeV assuming that the central value of the measurement agrees with the SM prediction (we will make this assumption for all cases to follow also). For a future integrated luminosity of 2.5 fb^{-1} combined over 4 detectors (combining $\sqrt{s} = 162 - 200$ GeV) and assuming that the error on the cross section is only statistical and the efficiency for detecting WW is 100% (it is likely to be about 80%), the future measurement will be $\approx 16 \text{ pb} \pm 0.08 \text{ pb}$. This gives a 2σ limit of $M_S \approx 1040$ GeV. ⁷

The differential cross sections for $e^+e^- \rightarrow ZZ$ are plotted in Fig.2. In this case, we integrate the differential cross section over $0 < \theta < \pi/2$ since we have identical final state particles. The preliminary results from the data at $\sqrt{s} = 189$ GeV are $\sigma_{ZZ} \approx 0.6 \text{ pb} \pm 0.06 \text{ pb}$ (we took the ALEPH error from [8] and divided it by 2 for the 4 detectors assuming it is dominated by statistics). This gives a 2σ limit of $M_S \approx 670$ GeV. A future measurement of $\sigma_{ZZ} \approx 0.8 \text{ pb} \pm 0.02 \text{ pb}$ is possible with 2 fb^{-1} summed over the 4 detectors at $\sqrt{s} = 189 - 200$ GeV, assuming that the error is statistical and the efficiency for detecting ZZ is $\approx 100\%$ (it likely to be about 50%). This will give a 2σ

⁷This is obtained by roughly scaling the present 2σ limit by a factor of (present error on σ)/(future error on σ)^{1/4} since (for the same \sqrt{s}) the deviation in cross section due to the graviton exchange, being mainly due to the interference between the SM and the graviton exchange amplitude, scales as M_S^{-4} .

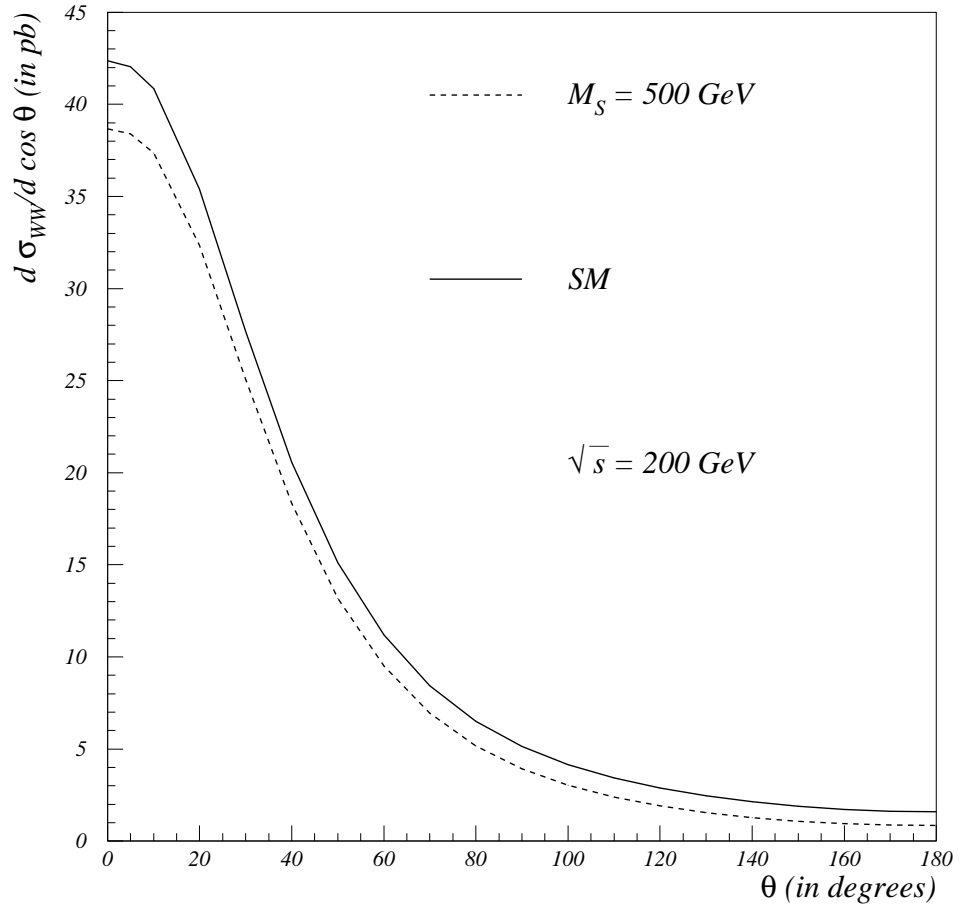


Figure 1: The differential cross section for $e^+e^- \rightarrow W^+W^-$ at $\sqrt{s} = 200$ GeV as a function of θ , the angle between e^+ and W^+ , in the SM and with the “string scale” = 500 GeV.

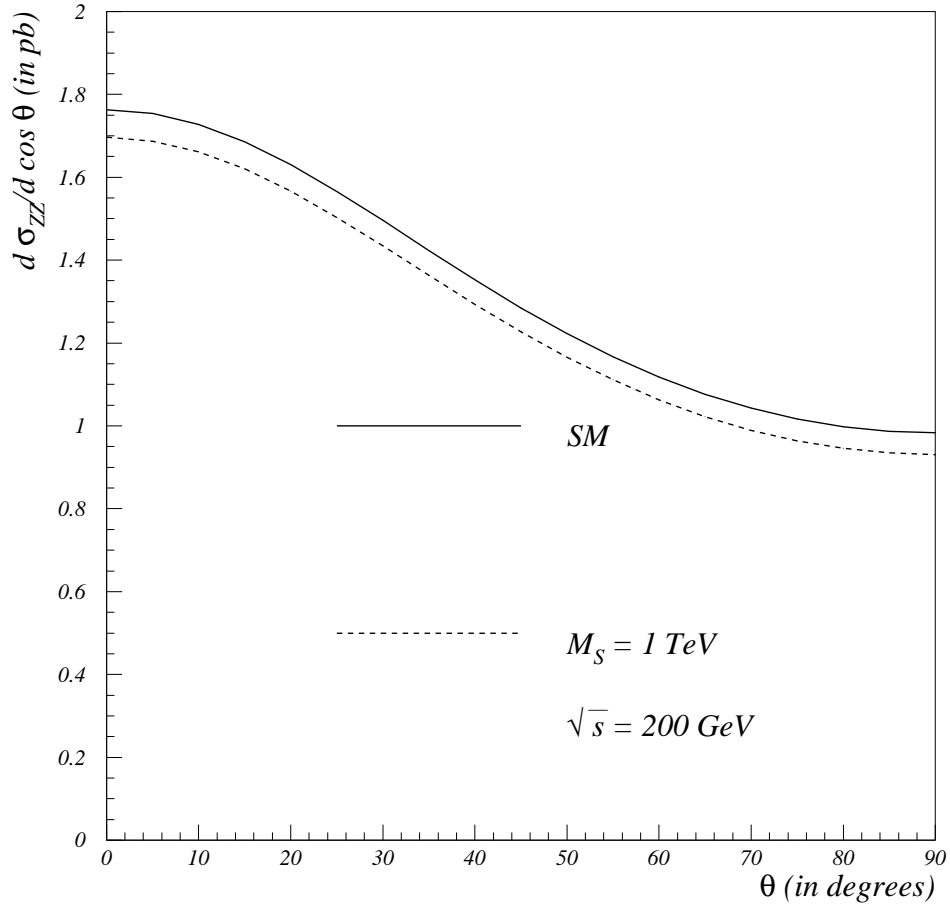


Figure 2: The differential cross section for $e^+e^- \rightarrow ZZ$ at $\sqrt{s} = 200$ GeV as a function of θ , the angle between e^+ and Z , in the SM and with the “string scale” = 1 TeV.

limit of $M_S \approx 980$ GeV.

At a LC with $\sqrt{s} = 500$ GeV with an integrated luminosity of 75 (fb)^{-1} , the measurements will be (with the same assumptions) $\sigma_{WW} \approx 6.6 \text{ pb} \pm 9 \text{ fb}$, $\sigma_{ZZ} \approx 0.38 \text{ pb} \pm 2.3 \text{ fb}$. We get a 2σ limits of $M_S \approx 2.8$ TeV (from WW) and 3 TeV (from ZZ).⁸

At a LC, it will be possible to use right-handed e^- beam so that the dominant SM amplitude for $e^+e^- \rightarrow W^+W^-$ due to the t -channel ν exchange can be suppressed. For $M_S \sim 1$ TeV, the gravity matrix element is larger (smaller) than the SM matrix element for e_R^- (e_L^-) so that the deviation from the SM cross section is (mainly) due to the (square of) the gravity matrix element for e_R^- whereas for e_L^- the effect is due to the interference between the SM and gravity amplitudes. Thus, (assuming that the experimental error is statistical), for $M_S \sim 1$ TeV, the statistical significance of the deviation in the cross section is larger for e_R^- than for e_L^- (or unpolarized e^-). However, for these values of M_S , the effect on the cross section with unpolarized e^- is already many standard deviations (it is an 8σ effect even with 1 (fb)^{-1}) and so it suffices to use unpolarized e^- beam. To obtain 2σ limits on M_S , we have to consider scales $M_S \gtrsim 2$ TeV for which the graviton exchange amplitude is smaller than the SM amplitude for *both* e_R^- and e_L^- so that the deviation in the cross section is due to interference between the graviton exchange and SM amplitudes for both beam helicities. Therefore, the 2σ limit on M_S obtained by using *unpolarized* e^- is comparable to the 2σ limits obtained by using polarized beams.⁹

⁸At $\sqrt{s} = 500$ GeV, imposing a cut $\cos\theta \leq 0$ (*i.e.* using the effect on the “backward” cross section) for WW and $\cos\theta \leq 0.9$ for ZZ increases the limit on M_S by about 250 GeV.

⁹For e_R^- beam, the SM differential cross section peaks in the central region ($\theta = \pi/2$) and has *no* forward-backward asymmetry. The interference between the SM and graviton exchange amplitudes (for e_R^-) is constructive (destructive) in the forward (backward) region (for $\lambda > 0$) resulting in a forward-backward asymmetry. Thus, to get a 2σ limit on M_S using e_R^- it is better to use the effect on the forward cross section (or the forward-backward asymmetry) rather than the total cross section.

For completeness, we show the limits obtained by considering $e^+e^- \rightarrow \gamma\gamma$. This case for a LC with $\sqrt{s} = 1$ TeV was discussed by Giudice, Rattazzi, Wells in [2]. Again, the graviton exchange matrix element is given by Eqn.(8) with $\beta = 1$ and the SM Born amplitude is given by Eqn.(14) with the electron coupling to Z replaced by the coupling to the photon. With only transverse polarizations for the photon, using Eqns.(10) and (11) with $\beta = 1$, the differential cross section simplifies to [2]:

$$\left(\frac{d\sigma}{d\cos\theta} \right) = \frac{\pi}{s} \left[\alpha G_1 \left(\frac{t}{s} \right) \mp \frac{4s^2}{\pi M_S^4} G_2 \left(\frac{t}{s} \right) \right]^2 \quad (15)$$

with

$$\begin{aligned} \frac{t}{s} &= -\sin^2 \frac{\theta}{2}, \\ G_1(x) &= \sqrt{\frac{1+2x+2x^2}{-x(1+x)}}, \\ G_2(x) &= \sqrt{\frac{-x(1+x)(1+2x+2x^2)}{16}}, \end{aligned} \quad (16)$$

where the \mp sign in Eqn.(15) corresponds to $\lambda = \pm 1$ in Eqn.(3). The differential cross sections for $e^+e^- \rightarrow \gamma\gamma$ are shown in Fig.(3). As expected the differential cross section has a strong forward peak (it diverges at $\theta = 0$ in the limit of $m_e = 0$). The measured cross section at $\sqrt{s} = 183$ GeV is [9] (again, we have reduced the error by a factor of 2 for the 4 detectors assuming that the error is statistical) $\sigma_{\gamma\gamma}(\cos\theta \leq 0.9) \approx 8 \text{ pb} \pm 0.2 \text{ pb}$ consistent with the SM prediction giving a 2σ limit of $M_S = 720$ GeV. With 2.5 (fb)^{-1} of data at $\sqrt{s} = 162\text{--}200$ GeV, the error will reduce to $\approx 0.06 \text{ pb}$ (assuming it is statistical) giving a 2σ limit of $M_S = 1060$ GeV. At a LC with $\sqrt{s} = 500$ GeV the measurement will be $1.07 \text{ pb} \pm 3.8 \text{ fb}$ giving a 2σ limit of $M_S = 3.2$ TeV.

To summarize, in Figs.4 and 5, we show the deviation from the SM cross section for $e^+e^- \rightarrow WW$, ZZ and $\gamma\gamma$ as a function of M_S , the quantum

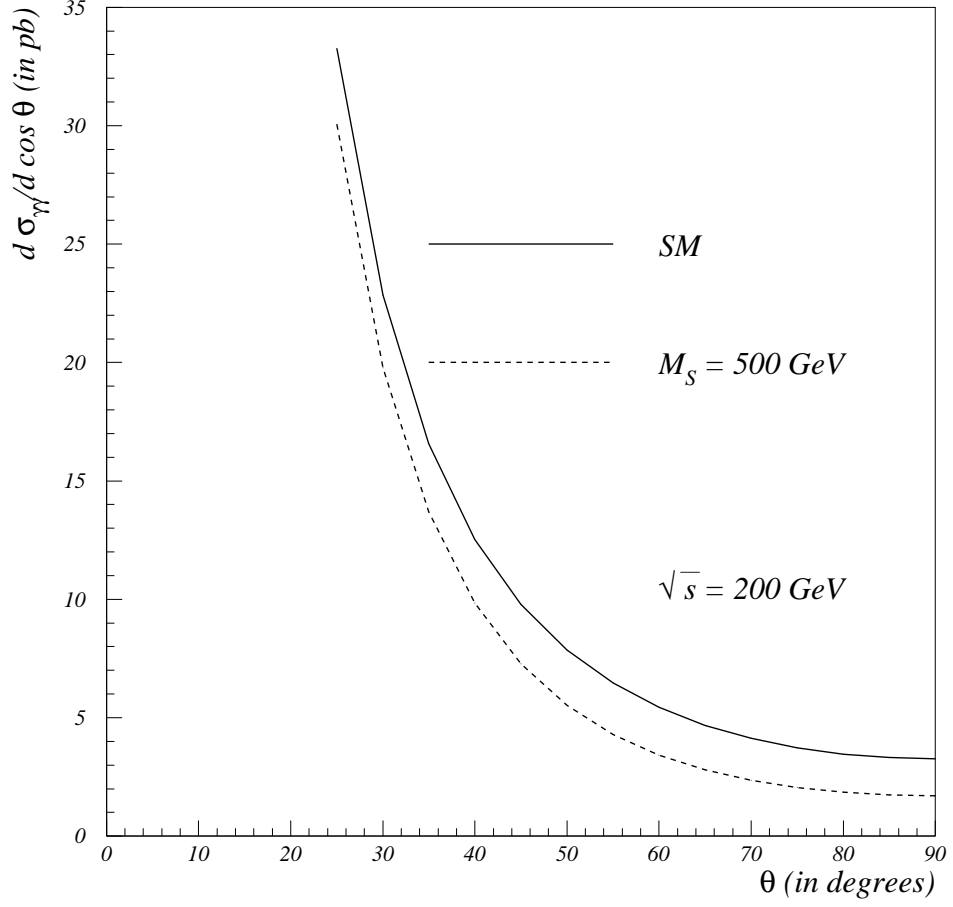


Figure 3: The differential cross section for $e^+e^- \rightarrow \gamma\gamma$ at $\sqrt{s} = 200$ GeV as a function of θ , the angle between e^+ and γ , in the SM and with the “string scale” = 500 GeV, for $\lambda = +1$ in Eqn.(3).

gravity scale (as defined in Eqn.(3)) for $\sqrt{s} = 200$ GeV (LEP2) and $\sqrt{s} = 500$ GeV (LC). We find that LEP2 with 2.5 fb^{-1} of data will be able to put a 2σ limit of $M_S \approx 1$ TeV (corresponding to experimental errors in the cross sections of about 0.5%, 2.5% and 0.7% for $e^+e^- \rightarrow WW, ZZ, \gamma\gamma$, respectively). This is comparable to the limits from $e^+e^- \rightarrow f\bar{f}$ at LEP2 [4] or the limits from the production of real gravitons at LEP2 obtained by Mirabelli, Perelstein, Peskin in [10].¹⁰

4 Acknowledgements

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¹⁰As mentioned earlier, the scale M_S defined by Eqn.(3) agrees with the notation used in [4]. It is related to the $(4+n)$ -dimensional Planck scale, M_{4+n} (as defined in Eqn.(17) of the second reference in [1]) by factors (of $O(1)$) which depend on the full theory. When comparing limits on TeV scale gravity from different processes, one should be careful about which scale, *i.e.*, M_S or M_{4+n} is used to derive the limit.

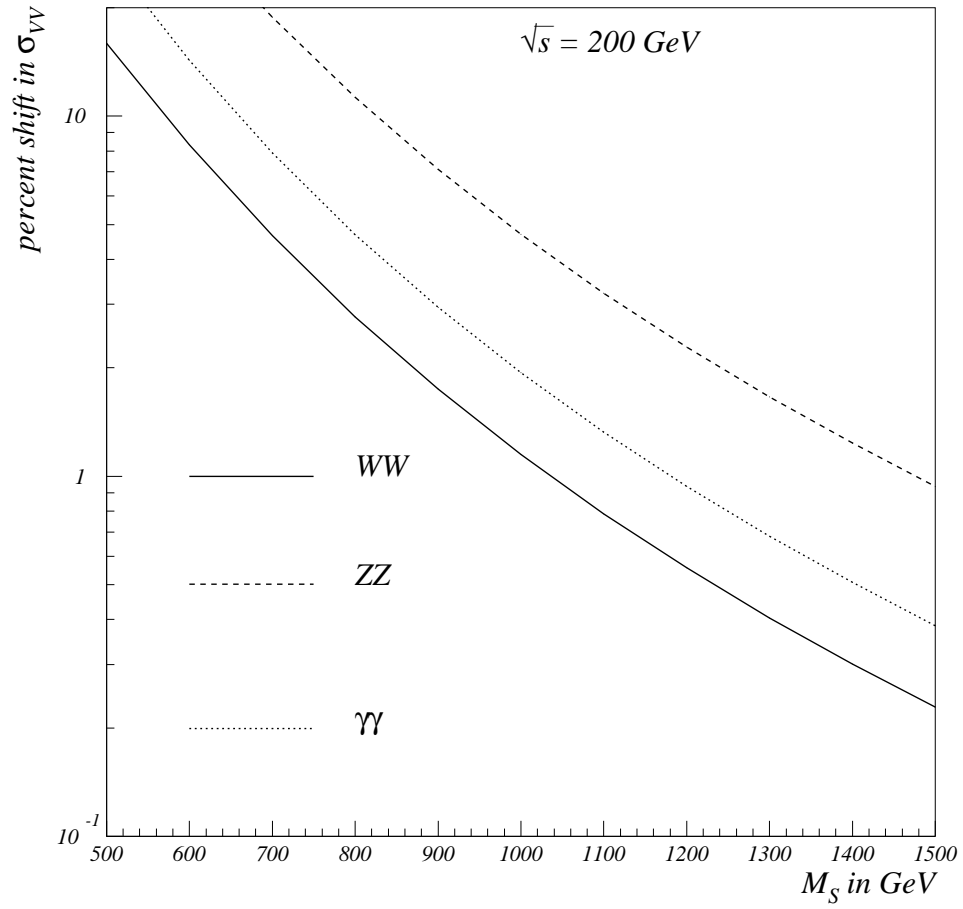


Figure 4: The deviations in percent of the cross section for $e^+e^- \rightarrow W^+W^-$, ZZ , $\gamma\gamma$ from the SM prediction as a function of the “string scale”, M_S at $\sqrt{s} = 200 \text{ GeV}$. For the $\gamma\gamma$ case, a cut $\cos \theta \leq 0.9$ is imposed.

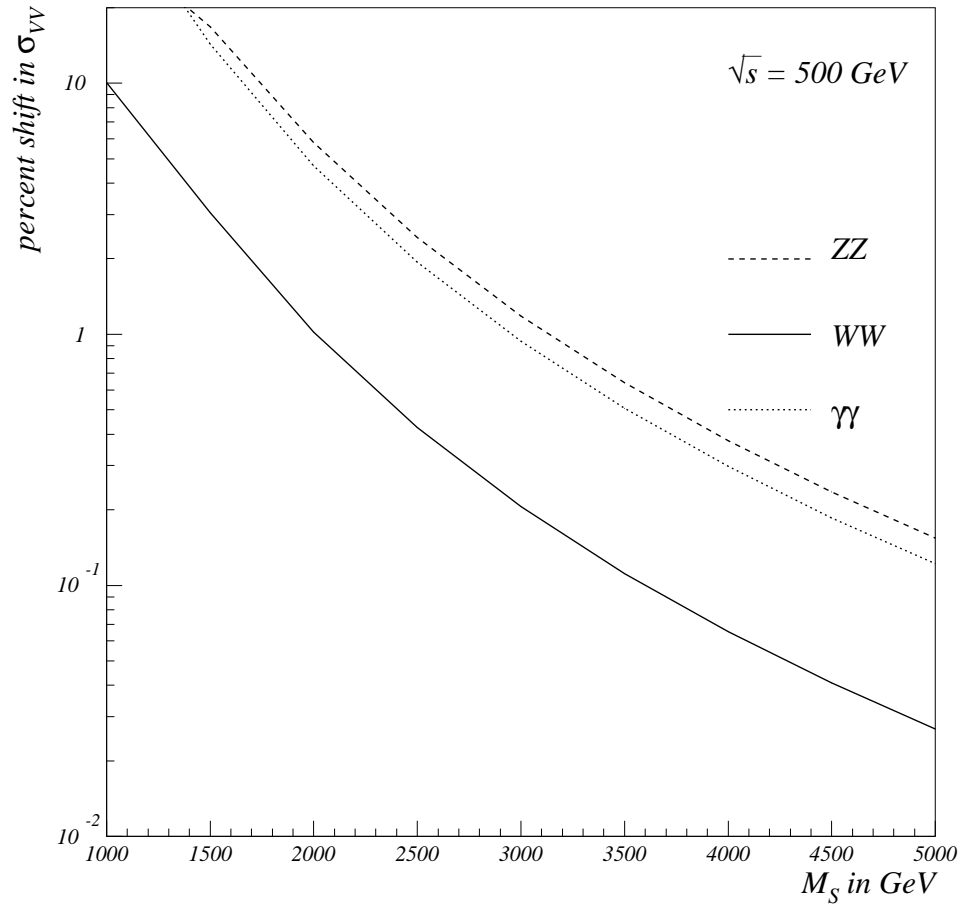


Figure 5: The deviations in percent of the cross section for $e^+e^- \rightarrow W^+W^-$, ZZ , $\gamma\gamma$ from the SM prediction as a function of the “string scale”, M_S at $\sqrt{s} = 500$ GeV. For the $\gamma\gamma$ case, a cut $\cos\theta \leq 0.9$ is imposed.

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